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Analysis of Risk and Dose when Using Thermal Protection on Non-Fissile and Fissile-Excepted UF_6 48-inch Cylinder Packages

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1.0 Background

An industry consortium of owners of large (*i.e.,* the 48-inch or 48X and 48Y) cylinders commissioned an independent study to evaluate the safety of using thermal protective covers on the cylinders and the likelihood that the cylinders would experience the regulations' hypothetical thermal accident. The study examined the demonstrable risks of the protective covers, *i.e.*, increased dose to workers and the potential for accidents associated with the extra handling, vs. the theoretical risk of the UF_6 cylinders' encountering the hypothetical fire, to evaluate the appropriateness of using the thermal protective covers.

One of the requirements of the IAEA regulations, *Regulations for the Safe Transport of Radioactive Material,* 1996 (Revised), TS-R-1, is that any uranium hexafluoride (UF_6) cylinder designed to contain 0.1 kg or more of material meet the thermal conditions of the regulations' hypothetical accident if Unilateral Approval is sought. The cylinder acceptance criterion is that the loaded cylinder sustains the thermal test environment for 30 minutes without rupture. The industry consortium mentioned above developed two designs to add thermal protection to these cylinders containing non-fissile and fissile-excepted UF_6.

One of these designs is for a blanket thermal protector (BTP), which is comprised of four separate pieces of insulating blanket that wrap both ends and middle sections between the cylinder skirts, leaving gaps for the support cradle. The pieces are held in place by fireproof straps and buckles. The weight of each piece is approximately 25 kg for the ends and 15 kg for the centers. The BTP is composed of a sandwich of several layers: the inner 11 mm insulator composed of refractory fiber cloth, and the outer surrounding shell made of 1 mm reinforced fire resistant textile with silicon coating.

The other design is for a composite thermal protector (CTP), which is comprised of eight separate rigid panels that clamp as a symmetrical top and bottom around both ends and middle sections between the cylinder skirts. The corresponding top and bottom pieces are connected with toggle catches. Removable fasteners hooked over the stiffening rings also secure each end. The CTP rests directly onto any supporting frame or cradle and is unaffected by the weight. The weight of each piece is approximately 32 kg for the ends and 28 kg for the centers. The CTP is composed of a rigid composite material formed from layers of silica cloth held together with resin. There is also a steel mesh running through the entire structure to give additional strength to fittings under fire conditions. The thin outer layer is of gel-coat, which gives a cosmetic smooth surface finish but has no effect on the structural or thermal properties.

In field testing of the protective covers, the sponsoring companies observed that, even with the relatively limited amount of time required to attach and/or detach the covers to/from the cylinders, increased dose to workers occurs and should be considered in the context of risk and benefit. While it is intuitive that extra handling means increased dose to workers and negative impacts to conventional safety, a specific study of these consequences was needed to evaluate those impacts. Similarly, a probabilistic risk analysis of the likelihood of a UF_6 cylinder becoming involved in a large transportation fire similar to that envisioned in TS-R-1 was needed for European shipments.

2.0 Probabilistic Safety Evaluation and Risk-Informed Discussion

The probabilistic safety evaluation was similar to the probabilistic risk assessment (PRA) that is commonly used in the evaluation of nuclear safety-related issues. Our safety evaluation only examined the expected frequency of occurrence and interval of the thermal test environment and the subsequent rupture of one or more cylinders. Radiological consequences of the rupture of cylinders were not quantitatively evaluated, although risk-informed data were offered on consequences.

"Risk-Informed" or risk insight is a concept whereby considerations other than purely numerical or analytical results may be used to comprehensively evaluate a risk circumstance. It allows the introduction of less quantifiable factors into the risk decision process. The fundamental safety argument must be soundly based on analyses and tests but the risk-informed elements help put things in perspective for a reasonable decision. [1]

3.0 Regulatory Considerations

TS-R-1 specifies the implementation and thermal test parameters of the UF_6 cylinder testing. TS-R-1 also authorizes the Competent Authority to approve the use of the large UF_6 cylinders without additional thermal protection. In fact, the TS-R-1 Advisory Material, TSG-1.1, acknowledges that, although the limitations of thermal performance modeling preclude an absolute prediction, the large cylinders "…*have been considered possibly to have sufficient thermal mass to survive exposure to the thermal test…without rupture of the containment system*."

Therefore, cylinders transported under an H(M) certificate are within regulatory compliance. Our report supports a Competent Authority's decision to issue an H(M) certificate by showing that the expected frequency of occurrence of the fire conditions during transport is acceptably low. That fact, plus the fact that use of additional thermal protective covers would increase the dose to workers and create negative impacts upon conventional worker safety, supports a decision to approve the use of the large UF_6 cylinders without additional thermal protection.

4.0 Modes Considered

The three modes considered for the evaluation were highway, railroad, and oceangoing vessel. These three modes, or combinations of them, are used in the transport of 48X and 48Y UF_6 cylinders in European and Russian commerce.

Highway: The highway transportation is via flatbed truck with shipping attachments mounted or on steamship line chassis with modified ocean containers. One or two cylinders are transported on each truck. European truck transports are conducted in compliance with the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR), as well as country-specific regulations.

Railroad: The railroad shipment of these cylinders is on flatcars with shipping attachments mounted. Up to four cylinders are contained on one rail wagon for European shipments and five cylinders per rail wagon (*i.e.,* railcar) for Russian shipments. In some cases up to 14 wagons are shipped in a regular freight train. In other cases a unit-train is used where as many as 50 wagons are placed in a dedicated train (*i.e*., no other cargo). European rail transports are conducted in compliance with the International Carriage of Dangerous Goods by Rail (RID), as well as country-specific regulations.

Oceangoing Vessel: The 48-inch UF_6 cylinders are shipped on oceangoing vessels (including ferries and coastal barges) in varying numbers. Routine shipments may involve from as few as three to as many as 150 cylinders. The larger numbers of cylinders are moved over longer distances in freighters. Cylinders shipped in freighter service are contained in one hold. For this study, shipments originating in North America were evaluated beginning at their *European* destination port because the transatlantic shipments from North America were taken into account in a risk evaluation conducted by USEC in the year 2000. [2] In one style of logistic, cylinders are transported in 20-foot flat-rack type ocean containers that have been modified with cradles and special tiedown points. Each container holds one cylinder. For shipments from North America to European ports, the ocean containers are shipped on container ships where they are stacked and secured. When they arrive at the European port, the cylinders remain on the flat-racks for ground transport by truck from the port to the processing facility. For ground transport by rail, although the cylinders may remain on the flat-racks, they are normally removed from the flat-racks and loaded onto rail wagons with cradles. Typically when cylinders are shipped in a bulk style logistic, the cylinders are not in flatracks for the ocean freight part of the trip. Upon arrival at the port in Europe, the cylinders are loaded onto a rail wagon or truck. In most cases, there is no intermediate handling of the cylinders between the shipping port and the destination port.

Some UF_6 cylinders are sent by barge (with from 24 to 75 UF_6 cylinders per barge) on a ship from North America to a European or Russian port. The loaded barges are transferred into an oceangoing mother ship in North America. At the European port, the barges are off-loaded from the mother ship and sent to feeder ports, where they are unloaded and sent onto the inland processing plants by truck or train.

Cylinders shipped by ferry remain on the original road trailer upon which they were loaded. A roll-on/roll-off technique is used and the cylinders/trailers are stowed on the ferry deck. When they reach the port, the cylinders are transported to the processing plants by truck or train.

5.0 Shipping Logistics and Matrix

Logistics: For purposes of this report, the logistical network considered consists of European shipments to/from the United Kingdom, the Netherlands, Germany, France and Russia. Oceangoing shipments to Europe from North America also are included, as described above. The logistical network consists of all loaded 48X and 48Y UF_6 cylinders moving among European locations by truck, railroad, and ship (including ferry and coastal barge). This report addresses only loaded natural and depleted UF_6 shipments in 48X or 48Y cylinders. Empty cylinders are excluded.

Shipping Matrix: Shipment data were gathered from European and North American UF_6 conversion and enrichment facilities. A summary of the data is given in Table 1, which encompasses the actual data and provides conservatism by increasing the values somewhat over the gathered data. This table only applies to those shipments defined above and accounts for all shipping segments. In many cases, several shipping modes are used to complete a shipment. It should be emphasized that Table 1 accounts for the number of shipments, not the number of cylinders shipped. The “Rail” rows of Table 1 are tabulated train-kilometers and rail wagon-kilometers. Recognize that these data are for the same shipments but are stated in different units. The two units were used to be compatible with accident statistic data that also are occasionally stated in these two terms. In the case of rail and water shipments, nominal values for the number of cylinders per vehicle/ship were assumed rather than the maximum values. This assumption accounts for the fact that not every shipment carries the maximum number of cylinders. It is a more realistic and conservative assessment of the total mode-kilometers and loaded trips.

Table 1 – Annual Shipping Data for the Loaded 48X and 48Y UF_6 Cylinders

Transport Mode	Mode-Kilometers	No. Loaded Trips	No. of Ports of Call
Truck	648,400	1,800	n/a
Rail – train	132,300	65	n/a
- car (wagon)	2,500,000	1,620	n/a
Ocean Vessel	132,300	170	340

The total number of 48X and 48Y cylinders represented by the Table 1 cannot be exactly determined due to the "rounding upward" of the actual shippers' data. A reasonable estimate of the Table 1 shipping volume is 3,500 cylinders per year. The number of cylinders shipped annually based on the survey of European conversion and enrichment facilities is 3,428 but the numbers are rounded upward for conservatism. The data for Table 1 were used to compute the expected frequencies of an engulfing fire and the subsequent assessment of cylinder rupture for each of the three modes.

6.0 Statistical Data on Accidents

The statistical data on European in-transit accidents that include an engulfing or severe fire are relatively sparse. The occurrence of a fire in an accident is generally a recorded statistic, and post-accident analyses attempt to describe the fire environment. However, important parameters such as fire extent, duration, and temperatures are rarely reported because of the difficulty in gathering such data or making a determination after-the-fact. Nevertheless, there are mode-specific accident data for several European countries. [3-9] These data were compiled and generally used in the analyses. In addition, these data were compared to transport mode accident rates in the United States. The average truck accident rate for Europe is almost identical to that of the USA. The average railroad accident rate for Europe is slightly lower than that of the USA. The reason for making these comparisons is to allow the use of select statistical methods based on USA data to supplement the European analyses. No ocean shipping comparison was necessary due to the availability of significant international and European data. [10]

Much of the USA statistical data on fire parameters are derived from probability theory, using Monte Carlo methods applied to factors that can contribute to the extent, duration and temperature of a fire. This makes the methodology largely independent of country, as long as the operation of the transport mode is similar to that in the United States. Indeed, the operations among countries involved in radioactive materials transport are similar, as all international shipping operations must comply with the packaging, labeling, marking, placarding, training and emergency response requirements of TS-R-1.

The application of accident statistics to the shipment of 48-inch UF_6 cylinders is complicated by the fact that the TS-R-1 fire is applied in the absence of any initiating events. In general land transport, however, the fire environment is created by other events, *i.e.*, an impact, crush or puncture of the transport vehicle in an accident. (This is not true for oceangoing vessel where fire is involved in less than 2% of the collisions.) Thus, probability studies tend to examine a sequence of events, one of which is fire. Because each event in an accident sequence has a conditional probability of occurrence, the sequence is far less likely than any one event. In reality there is some dependence between events so singling out one for study, *e.g.,* engulfing fire, tends to overstate its probability; spontaneous fires are extremely rare.

In our report, several methods of severe fire frequency prediction were used to estimate the actual value. [11-17] The bases of available accident data often vary and thus the resulting numerical values vary considerably. For example, some accident probabilities take into account accidents of all severities (*i.e.*, minor to major), whereas others have filtered out the minor events and only consider those of significance. Clearly the former will have a greater probability of occurrence than the latter. Where no valid data were available, engineering judgment was used for the analysis. After examining the various results, a risk-informed decision was made to converge on a reasonable value to be used for further analysis.

7.0 Risk-Informed Considerations

Cylinder Thermal Tests and Analyses: The (French) Institute for Nuclear Safety and Protection, IPSN, has conducted a series of experiments, called the Tenerife Project, to study the fire resistance of large-scale UF_6 transport cylinders. [18] The results of the testing program and the associated modeling done by individual countries under an IAEA Coordinated Research Program (CRP) have been inconclusive with respect to the accurate prediction of failure/non-failure. The various entities studying the response of a 48-inch UF_6 cylinder to an engulfing fire have bracketed the 30-minute fire duration with their predictions of cylinder rupture times. The CRP participants converged on a range of roughly 25-35 minutes as the time to reach the failure threshold. In the absence of other evidence, a 50-50 chance of failure was selected as a conservative measure. For conditional probability purposes in our study, we assumed that the rupture conditional probability was 0.5 for all modes.

Release Mitigation: There are several aspects to release mitigation. One aspect is that if cylinder rupture were to occur, it would not be explosive but rather a ductile tearing, followed by rapid depressurization. Depending on the size and location of the rupture, some evidence suggests that in the post-fire period, the contents may solidify and seal the failure site, thus limiting the release. This phenomenon is not a certainty, however.

Another aspect is that the one-inch fill/drain valve sealing is likely to fail during the fire and relieve some internal pressure. The valve failure and small leak would thus reduce the potential for cylinder rupture and a large leak. Although there is no consensus whether the pressure relief would be enough to prevent rupture, tests by Oak Ridge National Laboratory [19] and Japanese Central Research Institute of Electric Power Industry (CRIEPI) [20] have shown that valve leakage is an expected occurrence in an engulfing fire. The amount of UF_6 released through a failed valve is minimal. A valve leak has some likelihood of self-sealing in the post-fire period.

Release Consequences: A significant factor in reducing exposure of the general public to the radiological and toxicological effects of the UF_6 is the fact that the engulfing fire with its convective burning may elevate any released material for a wide downwind dispersion. A CRP researcher, Mr. Geoff Bailey of BNFL, has calculated that a 100 to 200 meter effective height of release (*i.e*., thermal lofting) results in a maximum combined ground level dose of hydrogen fluoride and uranium that "… *would not be expected to reach a level dangerous to life*." [21]

Another IPSN research program (*i.e*., PEECHEUR Programme) simulated the high temperature rupture of 48-inch UF_6 cylinders (but not containing UF_6). [22] The researchers determined that the failure may be smaller and in a different location than predicted by Bailey. However, it seems certain that some elevation and dispersion will occur due to thermal effects, regardless of the scenario.

A safety analysis performed by USEC for its two UF_6 plants considered a 48-inch cylinder failing in a large fire. [23] It determined that with an 8,000 pound (3,629 kg) release, the 30 mg Uranium uptake threshold occurs only 900 feet (274 m) from the release point, with lower values beyond 900 feet. This suggests that a severe toxicological hazard is localized and that the public at greater distances from the accident is not significantly at risk by a cylinder failure.

Finally, from IAEA, modal and other national regulations, the A_1/A_2 values for natural and depleted uranium are "unlimited," meaning that from a radiological safety perspective, there is a low radiological risk for the release of the UF_6 from a 48-inch cylinder.

8.0 Results Discussion

Analytical Results: Table 2 shows a summary of the results of the probability portion of our study. It shows that the expected frequency of occurrence of an engulfing fire that could lead to a subsequent rupture of an involved UF_6 cylinder is extremely low. These tabulated figures are thought to be conservative, *i.e.,* overstating the frequency. The engulfing fire is difficult to produce in tests; thus, the size of a real-world fire that could produce the time-temperature-exposure conditions of the regulations would have to be enormous. Such a conflagration is less likely than those defined in the "severe" fire category of the referenced reports.

Table 2
Estimated Severe Fire Frequencies and Intervals for
the Shipment of Loaded 48X and 48Y UF_6 Cylinders

Mode	Estimated Severe Fire Frequency per year	Estimated Severe Fire Interval, years
Truck	1.86×10^{-3}	537
Train	7.8×10^{-4}	1,282
Oceangoing Vessel	1.7×10^{-4}	5,882

Table 3 shows the maximum number of cylinders that might fail, given the transportation mode involvement in the severe fire. The associated frequencies range from 1×10^{-3} to 6×10^{-5}. Again, these are considered extremely low frequencies of occurrence.

Table 3 – Affected Number of Cylinders and Estimated Rupture Intervals

Mode	Estimated Max. Number of Ruptured UF_6 Cylinders	Estimated Rupture Interval, years
Truck	1	806
Train - one rail wagon	4	1,603
- two rail wagons	8	16,026
Oceangoing Vessel	8	5,882

Risk-Informed Considerations:

A U.S. Department of Energy (DOE) categorization of initiating event frequencies can be used to put expected frequencies of site operational conditions into perspective. The annual frequency range of 10^{-2} to 10^{-6} is used by the DOE for Evaluation Basis Events, which by definition "…*are not expected to occur during the life of a facility* …" This means that analysts only speculate on such occurrences for evaluation purposes *i.e*., there is no basis to believe that they actually will happen. All of the Table 2 and Table 3 accident frequencies for severe fire and subsequent cylinder rupture fall into this Evaluation Basis Events category.

USEC used the transportation hypothetical accident fire as a model for its large on-site fire accident environment. The analyses concluded that the risk to the general public (*i.e*., outside of the immediate accident vicinity) is within acceptable uptake guidelines. The BNFL study of a UF_6 release in a fire accident reaches essentially the same conclusion. [21]

Other risk-informed considerations mentioned above, *e.g.,* the self-sealing of the failure site and the unlimited A_1/A_2 value, suggest that even in the unlikely event of a release due to a fire accident, the radiological effects on the general public are acceptably low beyond the immediate vicinity of the event.

9.0 Dose Assessment

Field testing demonstrated that the installation and removal of the thermal protective covers increased the time required for cylinder loading/unloading operations. The purpose of the dose assessment was to quantify the incremental dose that the workers would receive as a result of using the thermal covers. Member companies sponsoring this study provided information on typical dose rates around filled UF_6 cylinders and on typical times required to install or remove the thermal covers. To capture the potential ranges of doses, distributions were assigned to the parameters used in the dose calculations. Representative values as shown in Table 4 were used in the dose assessment for both the BTP and CTP covers.

Table 4 – Dose Assessment Parameter Values

	Gamma Dose Rate (µSv/h)		Exposure times (min)		
Parameter	1 m	contact	Installation	Removal	Parameter Distribution
dose (uSv/h) and time (min):	10	15	20	15	mode of triangular distribution
range:	2 - 20	10 - 40	10 - 30	10 - 20	range of triangular distribution
workers exposed / cylinder:	-	-	2	2	
total cylinders handled/year:			3428	3428	200 to 300 for individual worker
neutron dose:	0				
thermal cover attenuation :	0				

The interaction of alpha particles from the uranium with the fluorine atoms also generates neutrons. However, since data indicated that the potential exposure of workers to neutrons was not high (< 2 ìSv/h), it was assumed that the neutron dose to workers was zero, which would tend to slightly underestimate worker doses. It was also assumed that the gamma radiation attenuation provided by the thermal protective covers would be negligible.

Two types of dose calculations were performed to estimate: (1) the incremental annual population dose summed over all workers involved with the installation and removal of the thermal covers; and (2) the incremental annual dose to a typical individual worker as a result of these activities. The population dose was considered a measure of the total additional risk to industry workers incurred as a result of the use of the thermal protective covers, while the incremental individual dose was considered a measure of the extra dose to individual workers installing or removing the thermal protective covers. All calculations were done probabilistically (10,000 trials) using *Crystal Ball* software [24]. Summary results are shown in Table 5.

Table 5 – Summary of Dose Calculations

Dose Calculated	Mean	Range (5% - 95%)
population dose (person-Sv/y)	0.065	0.040 - 0.096
installer dose (mSv/y)	1.35	0.72 - 2.19
remover dose (mSv/y)	1.01	0.59 - 1.56

Based on the ICRP detriment (risk) factor for cancer (fatal plus non-fatal cancers) for exposure of worker populations of 4.8% per person-Sv. [25] the estimated mean population dose of 0.065 person-Sv/y corresponds to a cancer risk of 0.0031 per year, or using the 95% population dose of 0.096 person-Sv/y, less than 0.005 per year for the entire worker cohort potentially involved with the installation and removal of the thermal covers. This suggests that the likelihood of a health impact to these workers as a result of these exposures, even assuming many years of potential exposure, is very small. The difference in the dose estimates to those installing (1.35 mSv/y) and removing (1.01 mSv/y) the thermal covers was due solely to the different exposure times assumed for these operations. These doses are small fractions of the 20 mSv/y dose limit for radiation workers. [25] However, considering that available data show that average doses to nuclear fuel workers tend to be about 10% of the occupational dose limit, the incremental annual dose to the workers handling the covers could be a significant fraction of their average annual exposures.

10.0 Conventional Worker Safety

Use of the thermal protection covers will substantially increase the safety risk to workers who handle the cylinders. The covers are large and cumbersome and the typical worker will be installing and removing the devices frequently. Both minor and major safety hazards are associated with the use of the covers. The design of the covers does not meet industrial safety recommended optimal conditions. The most significant hazard is the weight of the CTP because each section exceeds the recommended maximum lifting weight. Studies of workers' compensation claims have shown that manual material handling tasks, including lifting, are associated with back pain in 25% - 70% of injuries. [26-27] Bailey and Monk also have noted that the physical handling of the protective covers and their associated fastenings would impose additional risks of injury to transport system operators for every cylinder movement. After some observation of the handling risks, even with the use of some mechanical devices to assist with handling, the authors noted that these additional risks could outweigh the small and more hypothetical benefit of improved fire resistance the devices would offer. [28]

11.0 Conclusion

The study reported herein represents a conservative estimate of the occurrence of a severe fire environment during the transportation of UF_6 cylinders and the subsequent rupture of one or more units. The study showed that the cylinders would be unlikely to encounter the hypothetical thermal accident during hundreds to thousands of years of operations. Additionally, the dose study estimated that the use of special thermal protective covers would lead to an increased incremental dose for the typical worker installing or removing the covers. Given the low probability of a theoretical thermal accident, the demonstrated occupational safety impacts of using the thermal protective covers, and the unnecessary increased dose to workers, the study's conclusion is that the use of the covers is unwarranted and counterproductive.

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